The modelling of water restrictions applied in complex bulk water supply systems and the application of these techniques to operationalising the ecological Reserve

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Abstract

Water restrictions are often applied to users so as to limit the risk of failure of water supply systems during droughts. The models used in South Africa to date have applied this concept successfully to systems dominated by large dams, but little attention has been given to run-of-river users. An alternative methodology of curtailing users, and the modelling of this curtailment, is described in this paper. The enhancement over existing South African models introduced into the Water Resources Modelling Platform (WReMP) is that a unique curtailment rule is applied to each and every user modelled in the system. This curtailment can be linked to one of three drought indicators, the water level in a dam, the natural flow in the river (as modelled), or the actual flow in the river. The user need not be linked directly to the drought indicator, hence the scenario of applying restrictions to all users in a catchment during a drought, and not only those supplied by the dam, can be modelled. This is a practical scenario already applied, with varying degrees of success, in most South African catchments. Given the requirement in the National Water Act (Act 36 of 1998) of equitable water use, it is suggested that there is no alternative to this catchment-wide curtailment approach.

Curtailments during droughts is the more familiar concept of water use management. It is becoming increasingly clear, however, that curtailment rules will need to be established, especially applicable to run-of-river users, if the ecological Reserve requirements are to be met. The curtailment methodology described in this paper has been applied within WReMP on a catchment which is highly utilised by run-of-river irrigators. Theoretical curtailment rules were developed in order that the Reserve can be met. In this particular case, curtailment will require a change in cropping patterns in order to make low flows available for the Reserve. It is suggested that this or similar techniques will be required in order to operationalise the Reserve.

Keywords: *Water resources modelling, curtailment rules, operationalising the ecological Reserve.*

1. Introduction

In the ideal world bulk water supply systems would always be adequate to supply the water requirements for which they were designed. However, due to the uncertainty related to the temporal distribution of rainfall, there is always a risk of failure, however slight. In order to avoid complete and catastrophic failure of a water supply system, it is common practice to impose restrictions on water users when drought conditions are perceived. These restrictions or curtailments are generally applied at different times and at different levels to different users. Basson, et al (1994) describe curtailment as: '*During periods of limited water supply, decisions must be made to curtail water supply to some users in order to guarantee future water supply to other users*'.

In order to model the system as it is actually operated, a wide range of variability needs to be taken into account. A methodology to deal with this comprehensively within a time-series simulation has been developed, tested and applied in practice and is described in detail in this paper. The applicability of this method to operationalising the Reserve is demonstrated in this paper.

2. Curtailment methodologies applied in existing models

The water resources model used by most practicioners in South Africa is the Water Resources Yield Model (WRYM) (DWAF, 1998). This model, which is essentially an extension of the ACRES model developed in Canada (ACRES, 2004), until recently, could not explicitly deal with curtailments. Curtailing a water use would require representing the water user as two separate users, one of which is supplied when the dam is above a specified level, the other when the dam drops below this level. This method is at best cumbersome but becomes unmanageable if several curtailment levels are specified or water is supplied from multiple sources.

Curtailments and curtailment strategies are generally dealt with by WRYM modellers through the use of the Water Resources Planning Model (WRPM) (DWAF, 2000). This model is essentially an extension of WRYM to deal specifically with the short-term operation of reservoirs and the curtailments that this may require. It requires as input the yield reliability curves of each subsystem and these are produced using WRYM assuming no curtailments to users within the system. This methodology has been applied successfully to large systems such as the Vaal River System (Basson, et al, 1989). However, this system is not applicable to run-of-river users, or any user that is not supplied from the system. It is suggested in this

paper that the methodology used by WRPM is not applicable in systems which are significantly influenced by run-of-river abstractions or support from farm dams.

More recent developments of WRYM have incorporated two mechanisms for curtailing users. The so-called F15 file allows the user to apply curtailments to a demand file in up to ten pre-defined periods. This can be useful for short-term reservoir operation (for which it was developed) when the period of curtailment is known, but is of little use for planning purposes when the curtailment period is not known. It is conceivable that this method could be used iteratively, in which the curtailment period (based on, say, a reservoir level) is determined in the first simulation and then curtailments applied in the second simulation. Several iterations may however be required to achieve the desired operation of the reservoir, and if multiple users or multiple reservoirs are involved, this would not be practical.

The other curtailment mechanism is the F16 file, which simply allows the modeller to scale a user's requirements up or down by a factor. A feature of this methodology is that the desired assurance of supply can be defined and the model output indicates whether or not the supply criteria was met or not. The methodology requires many iterative runs in order to supply all users at the desired assurance of supply and in large systems can be very time-consuming. The main drawback of this methodology is that scaling a user up or down is very course and an intrinsically incorrect method of dealing with curtailments. In practice users are only curtailed during droughts and their maximum requirement would not be altered by the curtailment rule. Only in extreme cases, where the assurance of supply to user's is deemed too low to be sustainable, would the requirement itself be reduced, for example, by reducing the area of irrigated crop. To implement this in practice, however, would required compulsory licencing, a process that has not yet been applied in practice in South Africa.

Arguably the most widely used water resources model in the world is Mike Basins, developed and maintained by DHI Water and Environment based in Denmark (DHI, 2002). This model allows the modeller to define a curtailment rule for each user. These are typically linked to the reservoir from which the user is supplied or the river from which the user abstracts water. It does not appear to be possible within Mike Basins to curtail a water use based on a reservoir or river flow which is independent of the user.

3. Curtailment methodology applied within WReMP

3.1 Introduction

The curtailment methodology described here and implemented within the Water Resources Modelling Platform (WReMP) (Mallory, in progress) strives towards modelling the catchment as it would actually be operated. The following technical requirements are suggested as the minimum requirements to realistically model curtailments within a catchment:

- It must be possible to curtail all users in the catchment, regardless of their source of supply.
- Curtailment rules must apply to each and every user and need to take into account each users specific assurance requirements and the level of curtailment which ensures sustainable use from both an economic and environmental point of view.
- The curtailment needs to based on some practical and measurable indicator of the state of the water resource in the catchment. This would typically be the water level in a reservoir but could be the flow in the river (at any point) or the natural flow (as modelled) which is typically used as an indicator for ecological requirements.

3.2 Equitable curtailment throughout the catchment

The current operating strategy applied in most water supply systems in South Africa is that when the risk of complete failure becomes unacceptably high, the abstractions from the dam are reduced by applying restrictions to the users. However, users upstream of the dam and in tributaries are seldom curtailed and often enjoy a high level of assurance of supply. By applying restrictions to upstream users, the flow into the dam can be maintained during a drought and the yield of the reservoir increased. This approach would also result in a more equitable distribution of water during droughts.

3.3 Curtailment rules specific to each user

Water restrictions are not applied uniformly to all users in South Africa. Typically strategic and industrial users are seldom restricted due to the high economic cost that this would incur, while those less sensitive to restrictions in economic terms, such as urban users and irrigators, are curtailed by greater amounts. A typical priority classification system, as applied in the WRPM would be be as shown in Table 1.

Table 1: Priority classification system

Priority class	*Assurance of supply*
High	99,5 %
Medium	99%
Low	95%

Users are then categorised into sectors, such as Strategic, Industrial, Urban and Irrigation and the proportion of each priority class per sector defined.

This type of priority system has been used widely in South Africa and works well when applied to systems dominated by large reservoirs and users which are supplied from the reservoirs. A possible drawback is that a long period of operation is required in order to determine the actual assurance of supply that a user enjoys. The target assurance of supply is therefore a theoretical modelling concept to aid decision making and it is debatable whether the assurances are ever met in practice. The other aspect which is not clear, when restrictions are applied, what degree of curtailment will take place? A small restriction applied more frequently may be preferable to some users than large curtailments applied less frequently.

A suggested alternative to the priority classification system is a curtailment rule as shown in Table 2. Using this system, a user will have control over the degree of curtailment imposed on his use, which is, arguably, more important to most users than the frequency of the curtailment. The expected frequency of curtailment, or assurance of supply, can be estimated by means of time series simulation. This curtailment strategy has been applied within WReMP, an example of which is presented in section 4.

Table 2: Proposed curtailment rule

User	***Reservoir storage***		
	50 – 100%	***30 – 50%***	***0 – 30%***
Strategic	100% supplied	100% supplied	90% supplied
Industrial	100% supplied	90% supplied	80% supplied
Urban	100% supplied	80% supplied	60% supplied
Irrigation	100% supplied	50% supplied	30% supplied

The other concept applied in WReMP which deviates substantially from the curtailment strategies applied in WRPM is that a curtailment rule, as shown in Table 2, can be applied to each and every user as supplied from each and every source, while WRPM applies curtailments to sectors and not specific users. This will become increasingly important as competition for water grows in an economically expanding South Africa with limited water resources.

3.4 Curtailment rules linked to specific drought indicators in the catchment

The curtailment rule given in Table 2 is linked to the water level in a reservoir. In the case of run-of-river abstractions, the curtailment could be linked to the river flow rather than the storage in a reservoir. This is a concept which could be applied to ensure that ecological flow requirements are met by curtailing users during periods of low-flows.

3.5 Proposed curtailment methodology

From the above requirements, a curtailment method has been developed which allows the modeller to curtail each user (up to 5 levels of curtailment) based on one of the following criteria:

- *The water level in a dam*.
  This can be any dam in the system and the user need not necessarily be supplied from the dam used as the control mechanism.
- *The natural flow in the river*.
  This would typically be used for ecological flows.
- *The actual flow in the river*.
  This is a practical method to curtail users in uncontrolled catchments where users make use of run-of-river flows.

Figure 1 presents an example of curtailments based on water levels within a reservoir while Figure 2 presents an example of curtailments based on the flow in a river.

An example of a curtailment rule meeting the above requirements, as abstracted from the WReMP data input file, is given in Table 3.

In this particular example, the user sources his water firstly from run-of-river and if shortages occur, then sources water equally from 4 dams. Priorities can also be assigned to the dams in terms of supply to each user.

From a practical point of view, curtailments based on actual river flow offers a realistic mechanism to curtail irrigators and other users who make use of run-of-river. By rating the river section at which the user is abstracting, curtailment criteria can be converted to physical markers in the river bank which will make operation by the user much easier and control of each user becomes at least possible if not practical with the limited human resources available to catchment managers. Depending on the level of sophistication of the user, a number of curtailment level can be set, with the least sophisticated users limited

to a 'pump on' or 'pump off' instruction.

Table 3: WReMP Curtailment rule (for a single user)

Supplied from									
Source1: River		Source2: Dam 1		Source 3: Dam 2		Source 4: Dam 3		Source5: Dam 4	
Flow (% exceedence)	Supply	Dam Level (% FSC)	Supply	Level/ flow	Supply	Level/ flow	Supply	Level/ flow	Supply
0 - 40	100%	100 - 80	20%	100 - 80	20%	100 - 80	20%	100 - 80	20%
40 - 60	80%	20 -80	10%	20 -80	10%	20 -80	10%	20 -80	5%
60 - 80	60%	0-20	5%	0-20	5%	0-20	5%	0-20	2%
80 -100	0%								

The other important aspect of modelling curtailments is that under most circumstances curtailments must be applied on a seasonal rather than an annual basis. Practical examples of this are given in section 4.

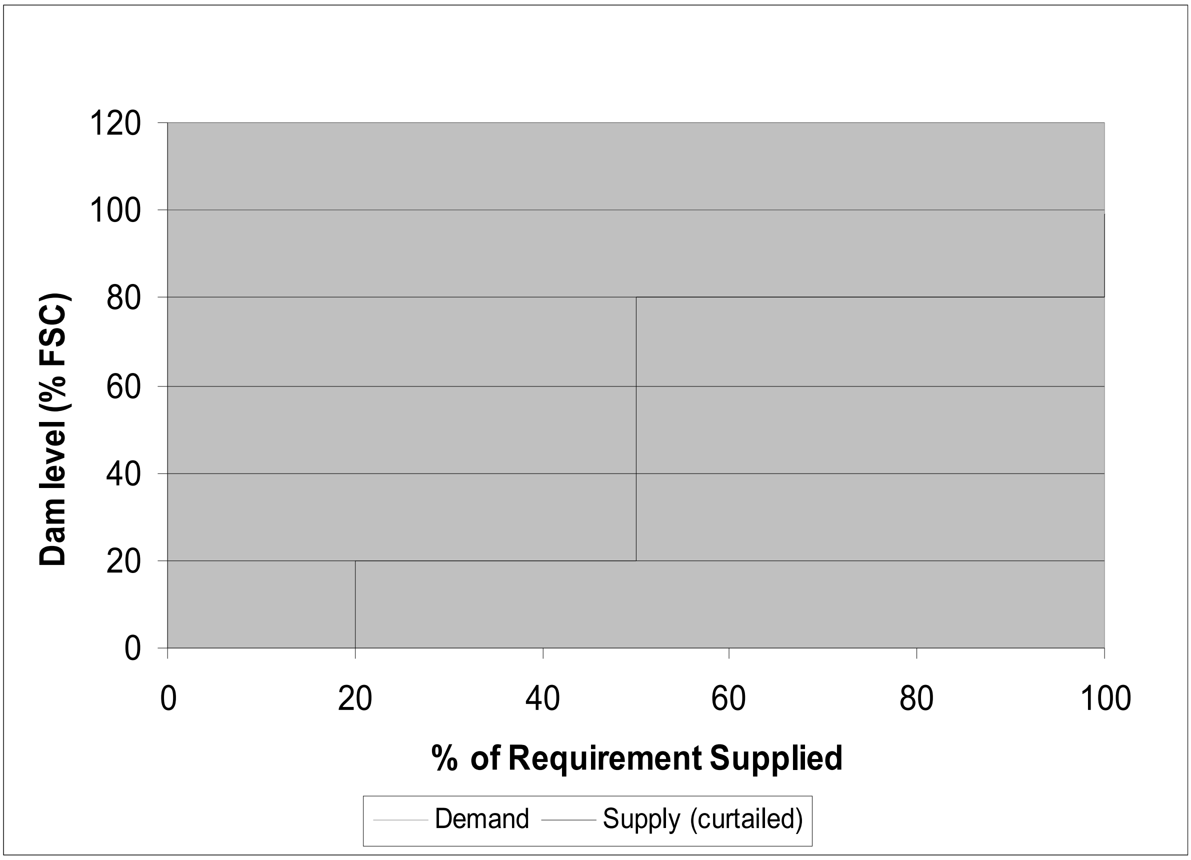


Figure 1: Curtailment as a function of the reservoir level

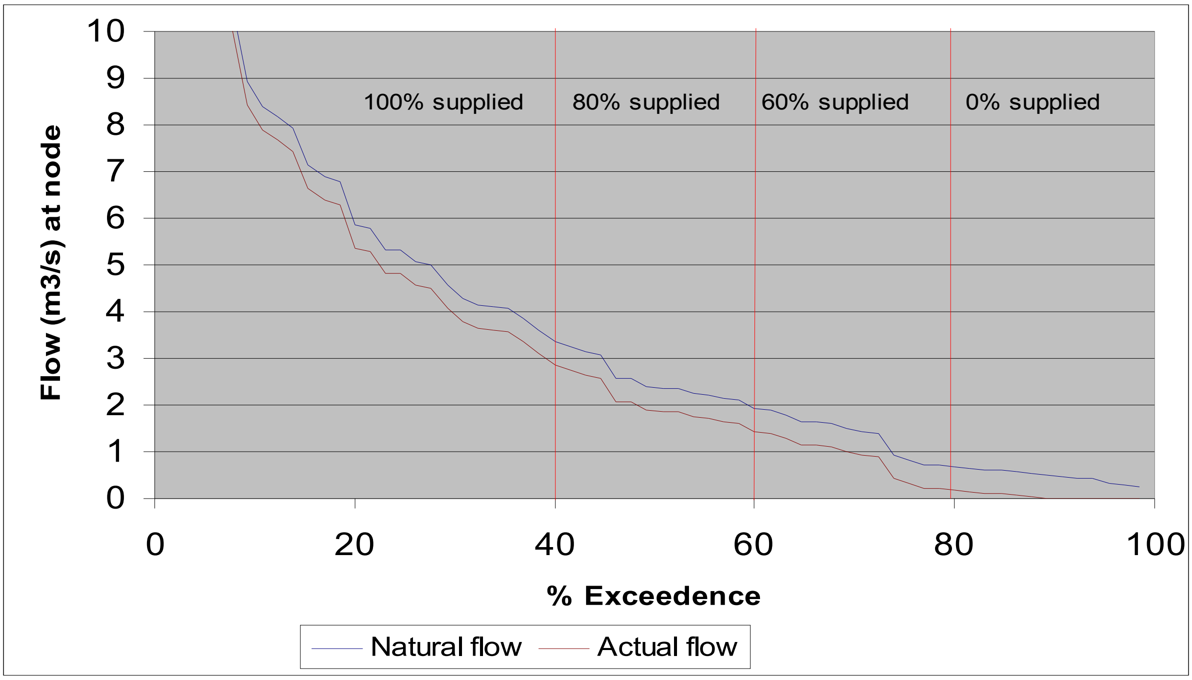


Figure 2: Curtailment as a function of natural or actual flow in the river

4. Practical application of the WReMP curtailment methodology

4.1 Planning analysis

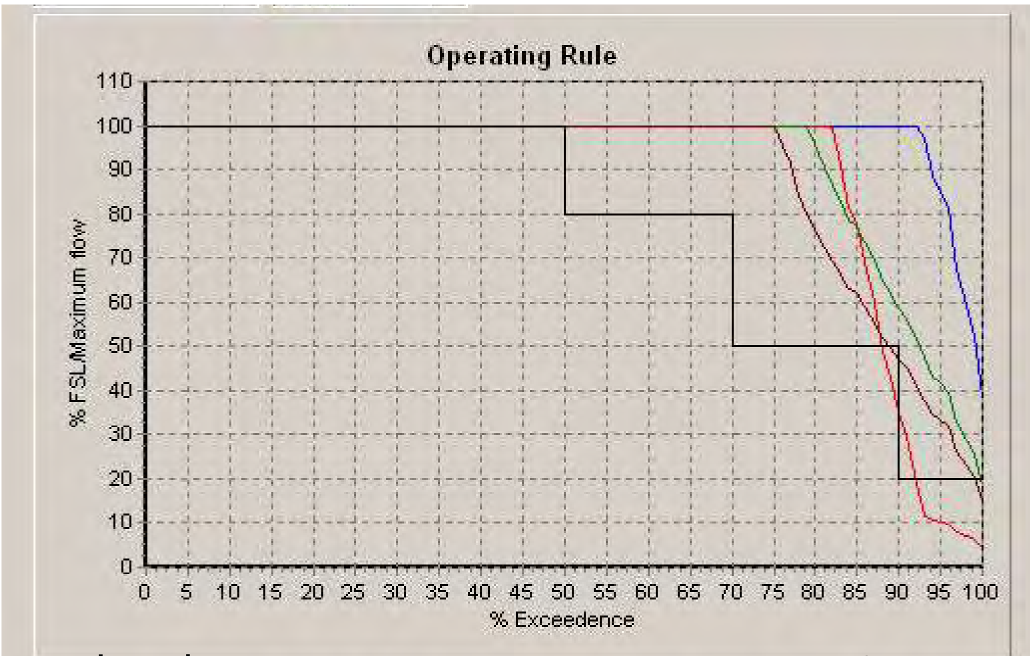
Apart from providing a more realistic planning tool in which the modelled catchment resembles actual operation and the consequences thereof more closely, the modelling of curtailments is going to become increasingly important in assessing the impact of the ecological Reserve scenarios on water users in a catchment. It will also be useful in assessing options relating to compulsory licencing. Curtailing users in the manner modelled by the WRYM F16 file will be the last resort and the preferred option will be a reduced assurance of supply to all users, which can now be assessed without having to resort to the costly and time consuming WRPM. The methodology described here can be used within a workshop environment using historical flow sequences and for more detailed planning, multiple stochastically generated sequences can be used to give a better indication of the long-term risk of failure or assurance of supply.

4.2 Reserve Determination and River Classification

The application of this curtailment method to Reserve determination, and the Reserve classification system presents the most obvious and practical application. When classifying a river reach for Reserve determination, it is essential that the social and economic consequences of the proposed classification be taken into consideration. These impacts relate to a reduction in water supply, and the importance of modelling this reduction using realistic curtailment rules is demonstrated here.

While the WRYM F16 methodology applies a curtailment to the whole time series in order to meet the assurance requirements, the same result can be achieved by only curtailing the requirement in certain months. Hence the economic impact could be much less than assumed by applying an annual curtailment.

An example of this concept is presented here. Figure 3 shows the supply to run-of-river irrigators before implementation of the Reserve. The irrigation requirements are mostly met at the required level of assurance, with only the low-flow requirements of the most downstream irrigator not being met. Figure 4 shows that the ecological requirement under these conditions cannot be fully met, with significant shortages in the low-flow months of July through to November. In the second scenario, the ecological Reserve is modelled as having priority over the run-of-river irrigators. Figure 5 shows how under these circumstances the assurance criteria of the irrigators cannot be met, and in order to meet it would require almost complete curtailment of the irrigation requirement, *if applied uniformly in all months.* The monthly distribution of the supply and demand (see Figure 6) shows that the irrigation shortages are mostly in the months of July through to October, with the irrigation requirements in the months of December through to June being fully met.. It is therefore not necessary to curtail irrigation use completely, but only in those months in which the supply to irrigation is not sustainable. Applying curtailments to upstream run-of-river irrigators, as summarised in Table 4, results in the ecological requirements being fully met, as well as the supply criteria of irrigation (see Figure 7). On average, this reduced the water supply to irrigators by 45%, compared with 97% required if curtailments are applied annually and not in each month.



Legend: The black stepped line represents the desired assurance of supply while the other four lines represent the assurance of supply to the four run-of-river irrigators in the catchment

Figure 3: Irrigation supply before implementation of the ecological Reserve, expressed as a duration curve

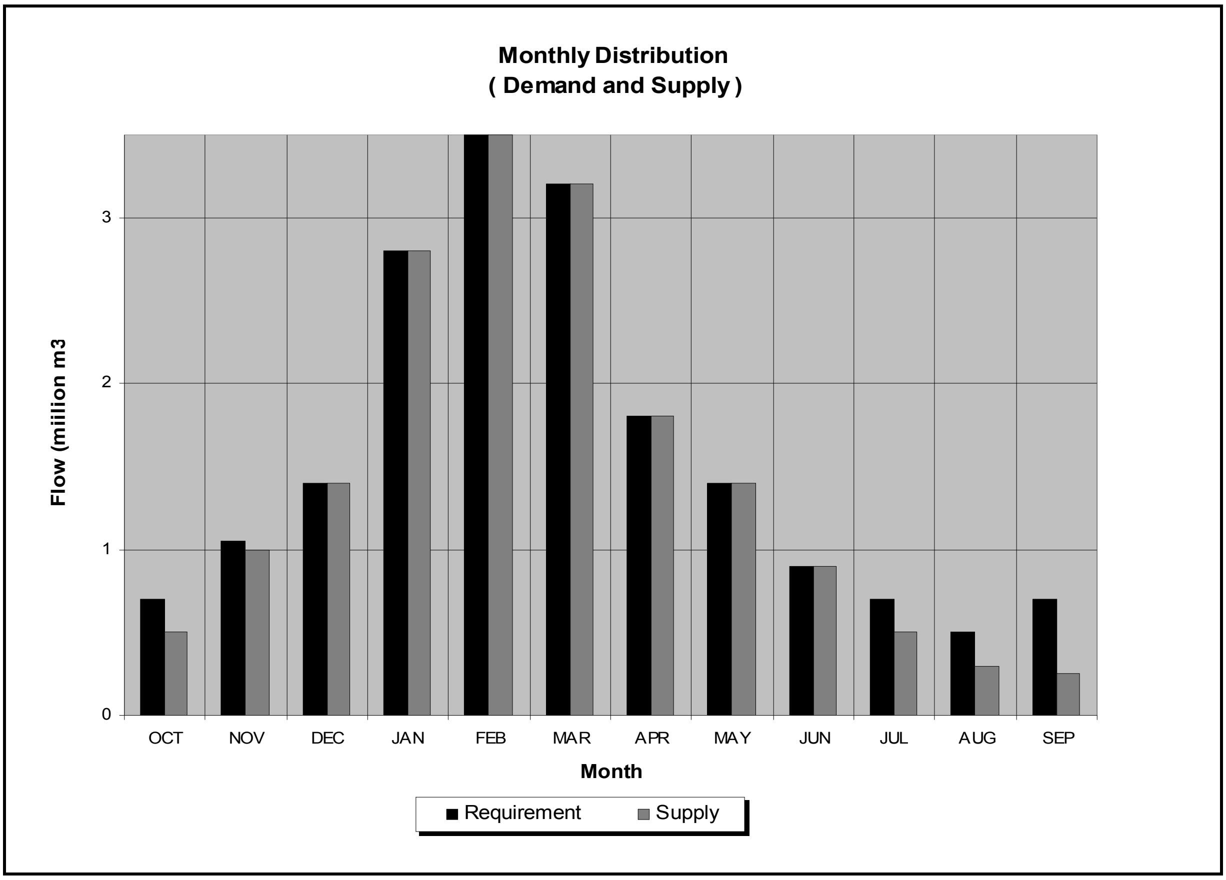
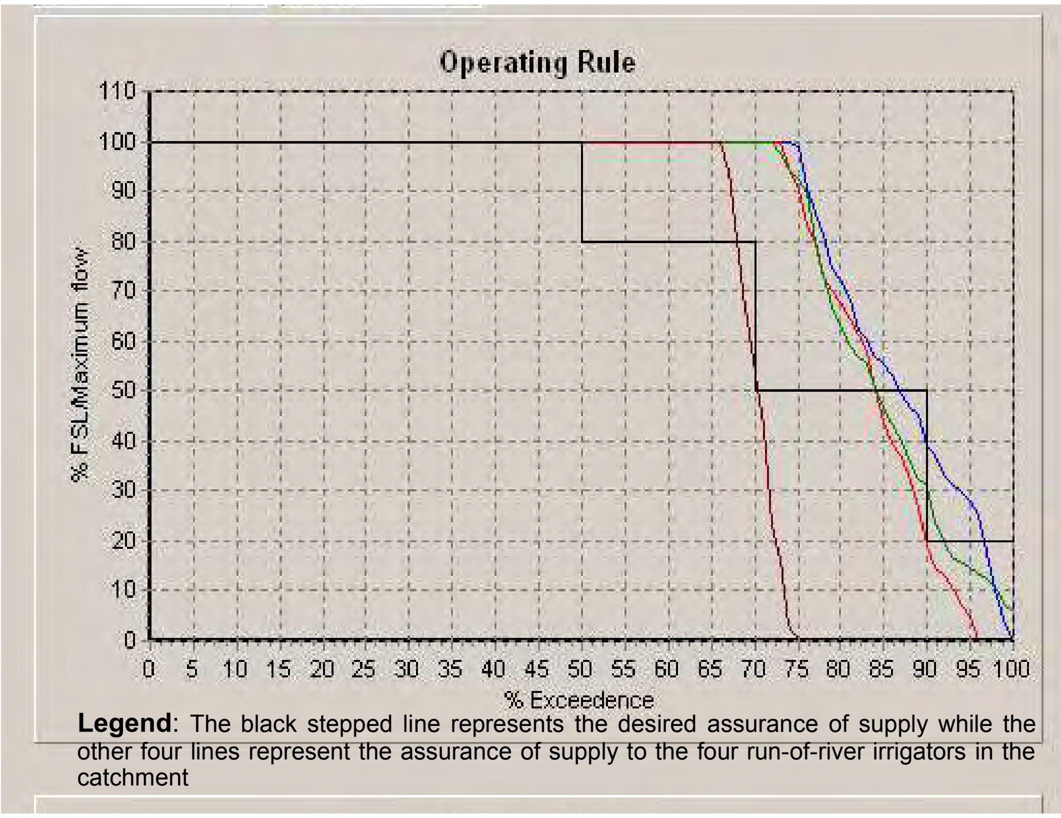


Figure 4: Monthly distribution of the ecological Reserve (requirement and supplied) before implementing any measures to meet the Reserve.



Legend: The black stepped line represents the desired assurance of supply while the other four lines represent the assurance of supply to the four run-of-river irrigators in the catchment

Figure 5: Irrigation supply after implementation of the ecological Reserve, expressed as a duration curve

Note that the supply duration curves in Figure 5 do not assume any specific operating rule to meet the Reserve. The Reserve is supplied as a priority by curtailing upstream use whenever the Reserve is not met. An operating rule such as this would be very difficult, if not impossible, to apply to multiple run-of-river abstractions within a catchment. The WRYM applies a rule such as this through a so-called 'penalty structure', and while this is a useful modelling concept for planning purposes, it is suggested that the penalty structure method of prioritising water supply to users does not relate well to the actual day to day operation of a catchment.

Based on the WReMP time series simulation, the minimum requirement specified in terms of assurance of supply to the irrigators cannot be met if the Reserve is to be met as a priority. See also Figure 6 which indicates shortages in the months of July through to October. Irrigation will therefore not be sustainable and a curtailment rule needs to be established to meet the assurance criteria.

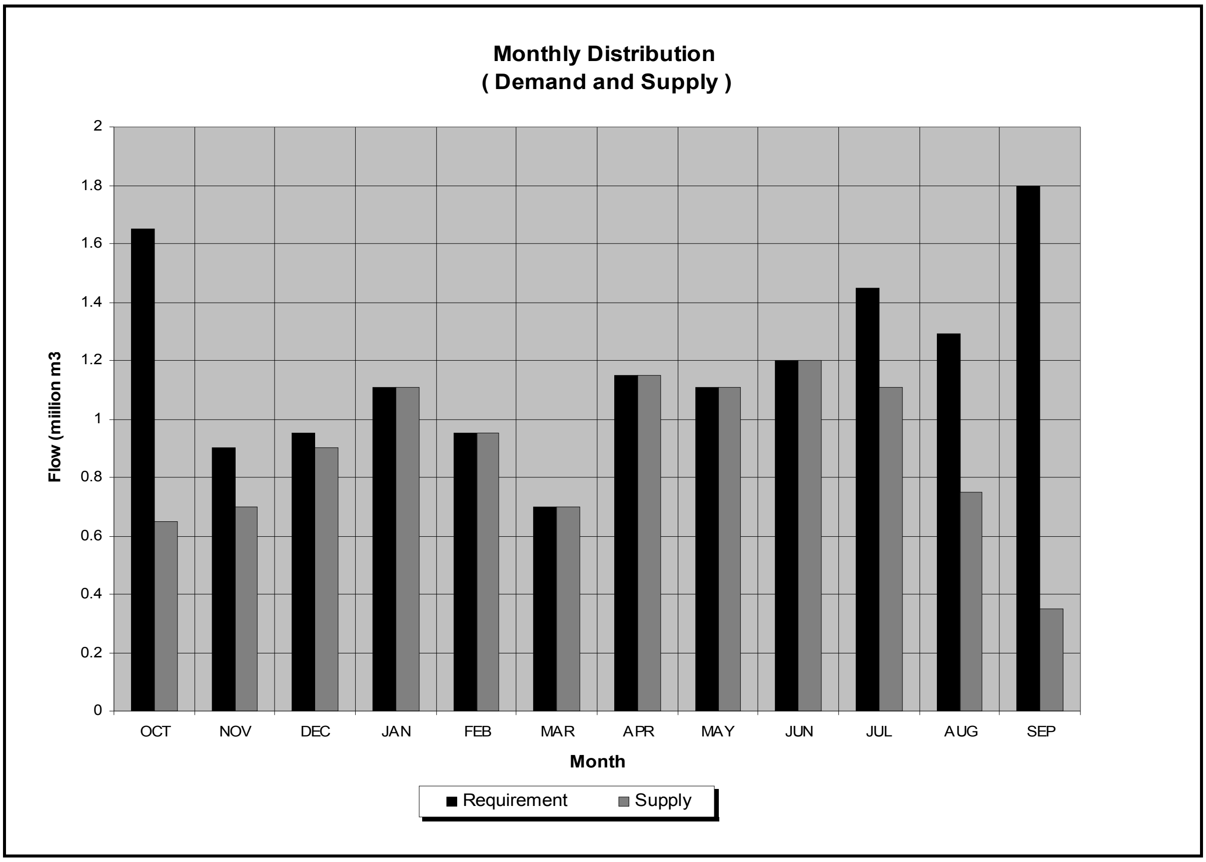


Figure 6: Monthly distribution of the water requirements and supply to irrigation

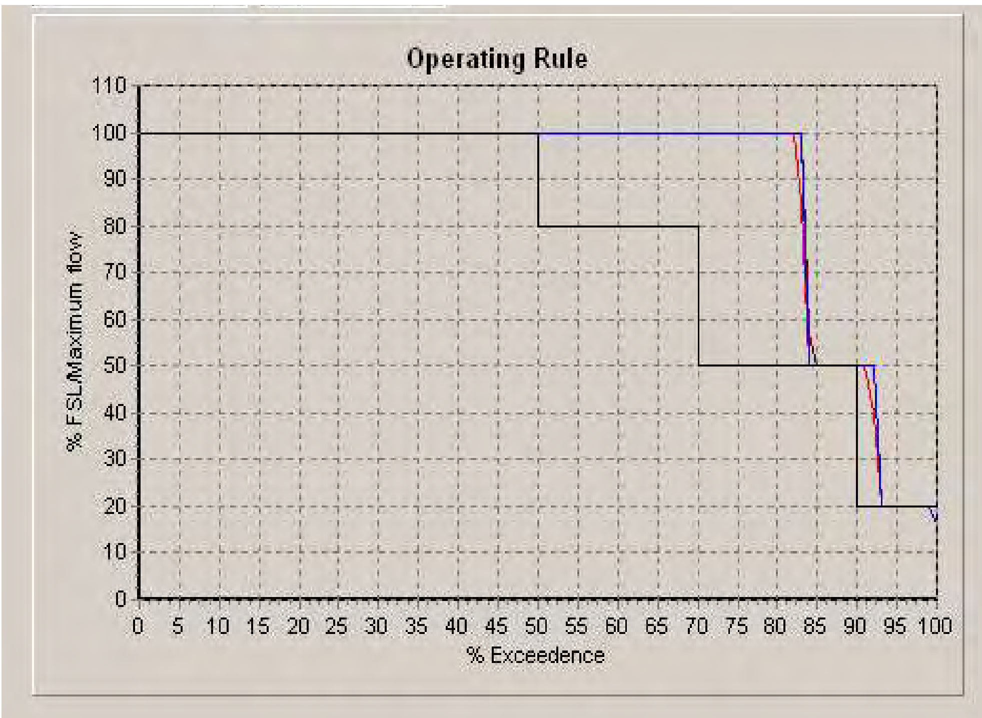


Figure 7: Irrigation supply after implementation of curtailment rules

Table 3: Comparison of WRYM and WReMP curtailments

Month	***WRYM curtailment***	***WReMP***
October	97%	100%
November	97%	80%
December	97%	0%
January	97%	0%
February	97%	0%
March	97%	0%
April	97%	0%
May	97%	0%
June	97%	0%
July	97%	50%
August	97%	100%
September	97%	100%
Weighted average	***97%***	***45%***

5. Discussion of Results

It is clear from Table 3 that by applying a curtailment rule to every month, the calculated economic impact will be considerably less than if a uniform annual curtailment is applied. The practical implementation of this could involve the cessation of irrigation in the months of August, September and October with an 80% curtailment in November and a 50% curtailment in July, while the remainder of the year would remain unrestricted. The total reduction in supply to irrigators would then be 45% on average (weighted) as apposed to the 97% obtained using an annual curtailment rule.

6. Conclusions

A method to model the curtailment of water use to the same level of detail as applied in practice within a catchment is presented in this paper and tested against an actual example. The impact of simplifying assumptions relating to the operationalising of the Reserve and the economic implications that this would have are shown to be large. The conclusion reached is that it is essential to consider curtailments on a monthly basis since by assuming uniform annual curtailments the curtailment required to meet the ecological Reserve can be grossly over estimated. As a result an overly pessimistic view is given of the socio-economic impact of the Reserve on existing water users. This will lead to incorrect selection of the management class of the river.

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